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Title: Searches for violations of fundamental symmetries

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Searches for violations of fundamental symmetries

Kaori Fuyuto

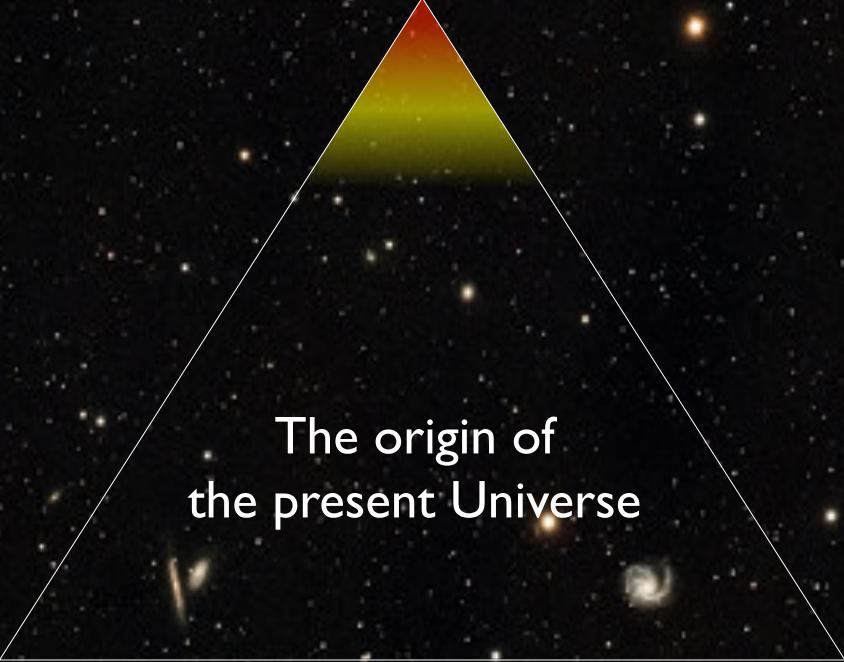
Los Alamos National Laboratory



J. de Vries, P. Draper, **KF**, J. Kozaczuk, D. Sutherland, PRD015042(2019)99
J. de Vries, P. Draper, **KF**, B. Lillard, PRD104(2021)055039
KF, W.S. Hou, and E. Senaha, PLB 776 (2018) 402, PRD101(2020)011901
V. Cirigliano, **KF**, C. Lee, E. Mereghetti, B. Yan, JHEP03(2021)256

January 20, 2022
LA-UR-22-

The Standard Model of Particle Physics is currently the best theory to describe the most basic building blocks of the Universe.



The origin of
the present Universe

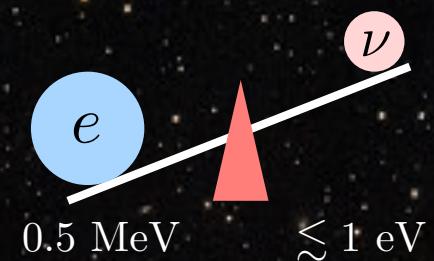
However, it does not explain the complete picture.

For example, the following questions are not answered by the SM

What is Dark Matter?



What is the origin of tiny neutrino mass ?



The origin of
the present Universe

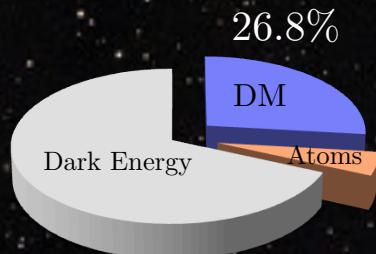
Why is there more matter than antimatter?
$$\frac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$$

*We need physics beyond the Standard Model.
(BSM Physics)

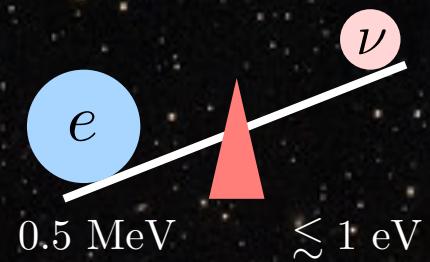


Key approach : Fundamental symmetry tests

What is Dark Matter?



What is the origin of tiny neutrino mass ?



**The origin of
the present Universe**

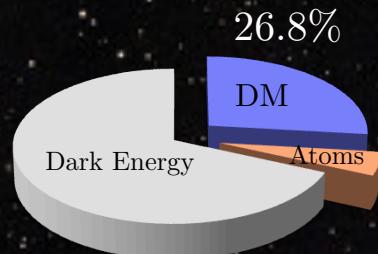
Why is there more matter than antimatter?
$$\frac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$$

Ex) Search for CP violation, Lepton Flavor and Lepton-Number Violation

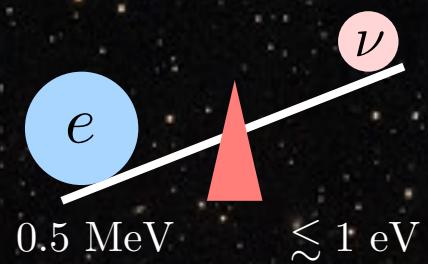


Key approach : Fundamental symmetry tests

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The origin of
the present Universe

Why is there more matter than antimatter?
$$\frac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$$

Today

Ex) Search for CP violation, Lepton Flavor and Lepton-Number Violation

CP violation

Search for CP violation

A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5, 32 (1967)

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CP violation is necessary to produce the Baryon Asymmetry of the Universe.



Search for CP violation

A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5, 32 (1967)

CP violation is necessary to produce the Baryon Asymmetry of the Universe.



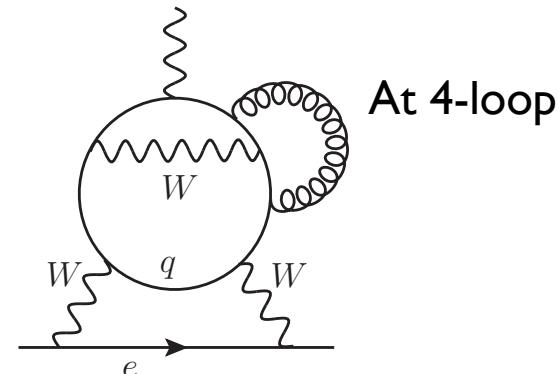
CPV source (needed for the BAU) can generate Electric Dipole Moments:

$$H_{\text{EDM}} = -d \frac{\mathbf{s}}{|\mathbf{s}|} \cdot \mathbf{E} \quad \mid \quad \mathbf{E} : \text{Electric field} \quad \mathbf{s} : \text{Spin}$$

Ex) Electron EDM in the SM

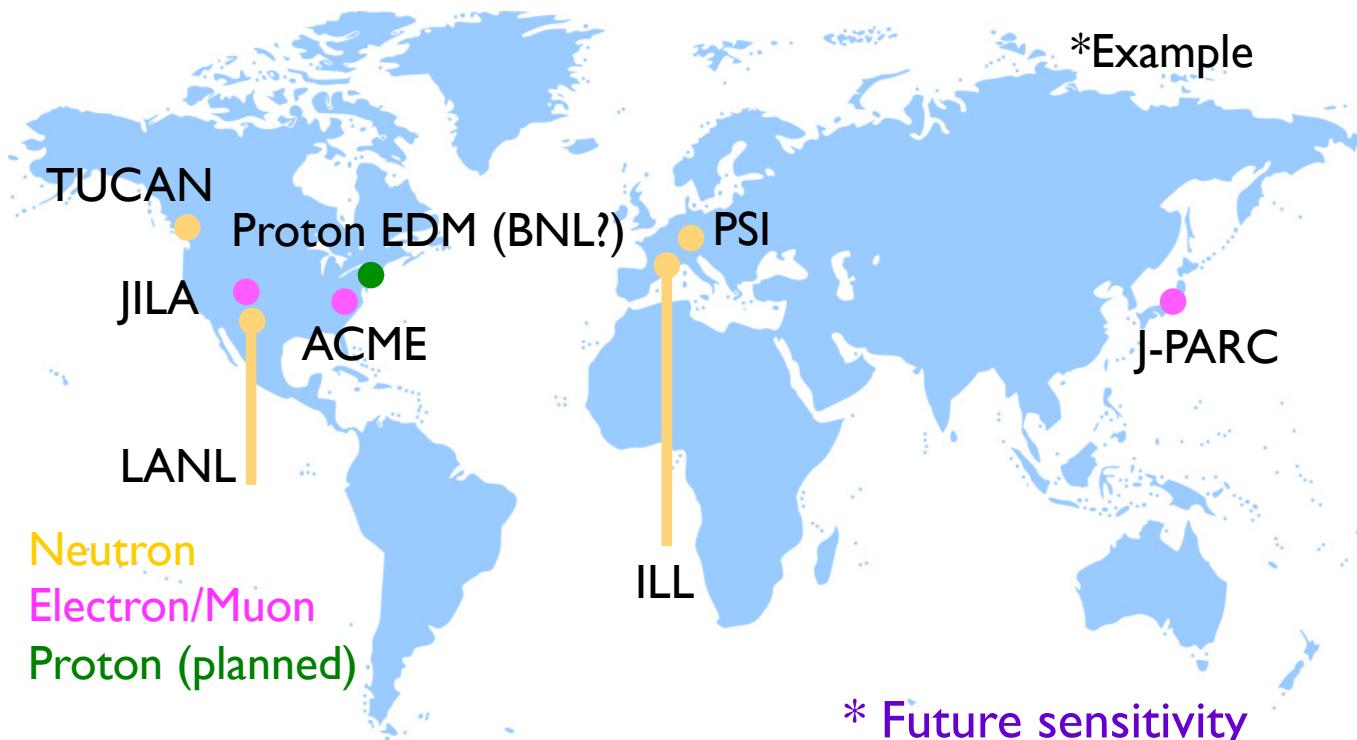
$$d_e^{\text{CKM}} \sim O(10^{-44}) \text{ e cm}$$

M. Pospelov, I.B. Khriplovich, SJNP53(1991)638, Yad. Fiz. 53(1991)1030
 D. Ng, J. Ng, Mod. MPLA11(1996)211, W. Bernreuther, M. Suzuki, RMP63(1991)313
 M. Pospelov and A. Ritz, PRD89(2014)056006



Various searches for EDMs

Various searches for EDMs are ongoing and planned.



$$|d_e| < 1.1 \times 10^{-29} \text{ e cm}$$

ACME Collaboration : Nature 562(2018)7727

$$|d_n| < 1.8 \times 10^{-26} \text{ e cm}$$

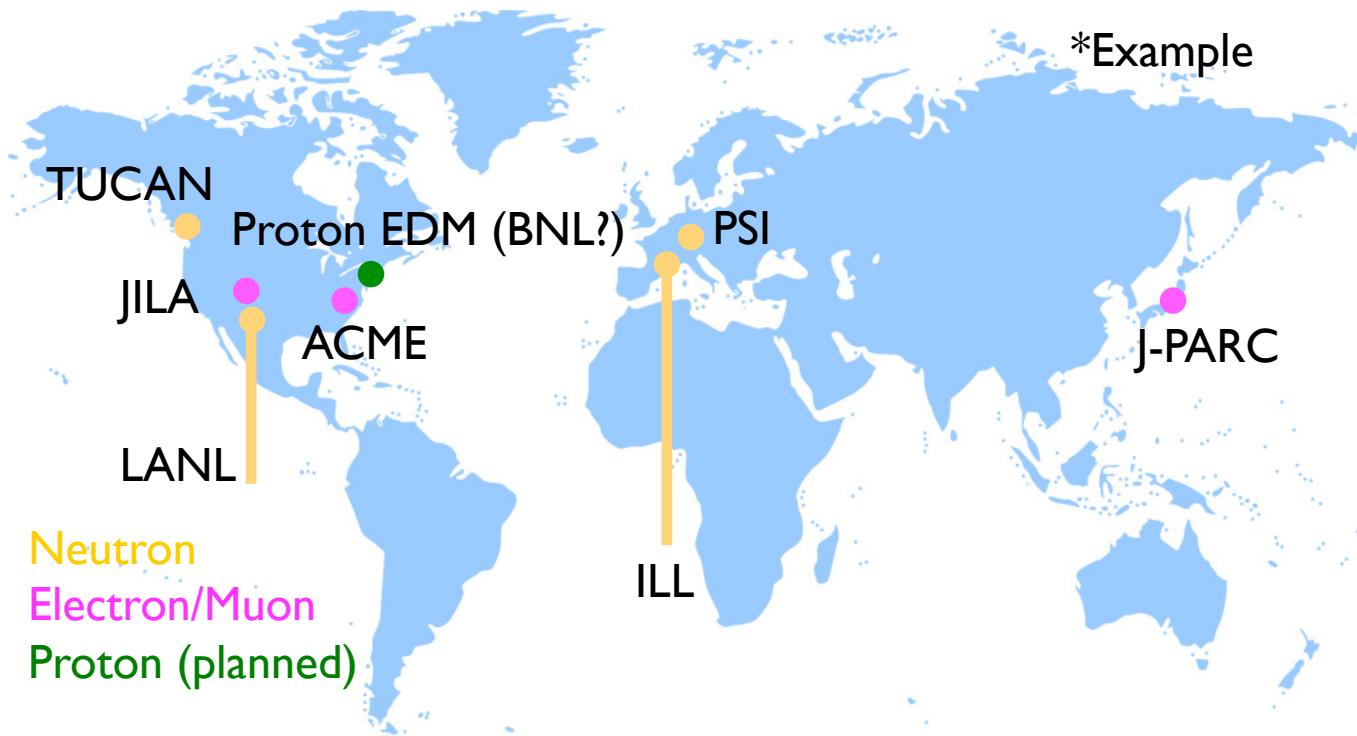
nEDM Collaboration, PRL124(2020)081803

$$\sim 10^{-30} \text{ e cm}$$

$$\sim 10^{-(27-28)} \text{ e cm}$$

Various searches for EDMs

Various searches for EDMs are ongoing and planned.

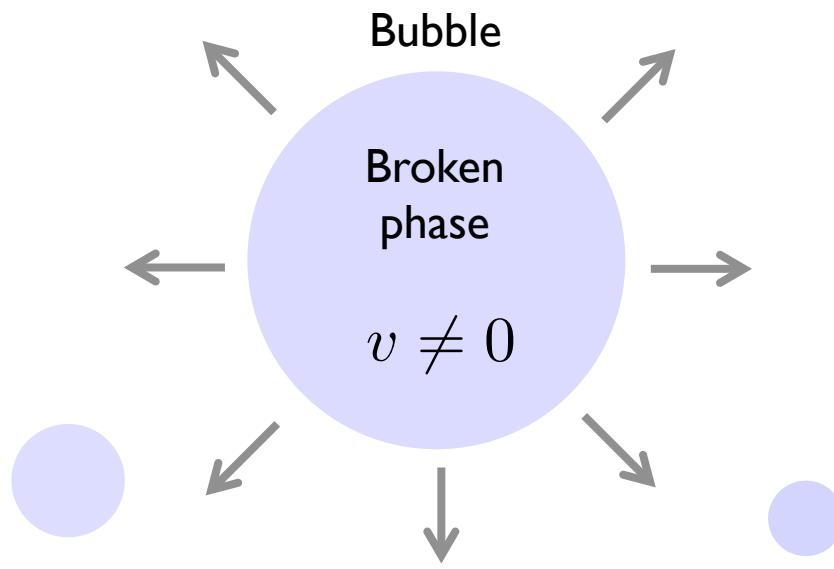


How do EDM searches play a role in solving the mystery of the BAU?

*One possible mechanism : Electroweak Baryogenesis

Electroweak Baryogenesis

Baryon asymmetry is created during EW phase transition.



Symmetric phase
 $v = 0$

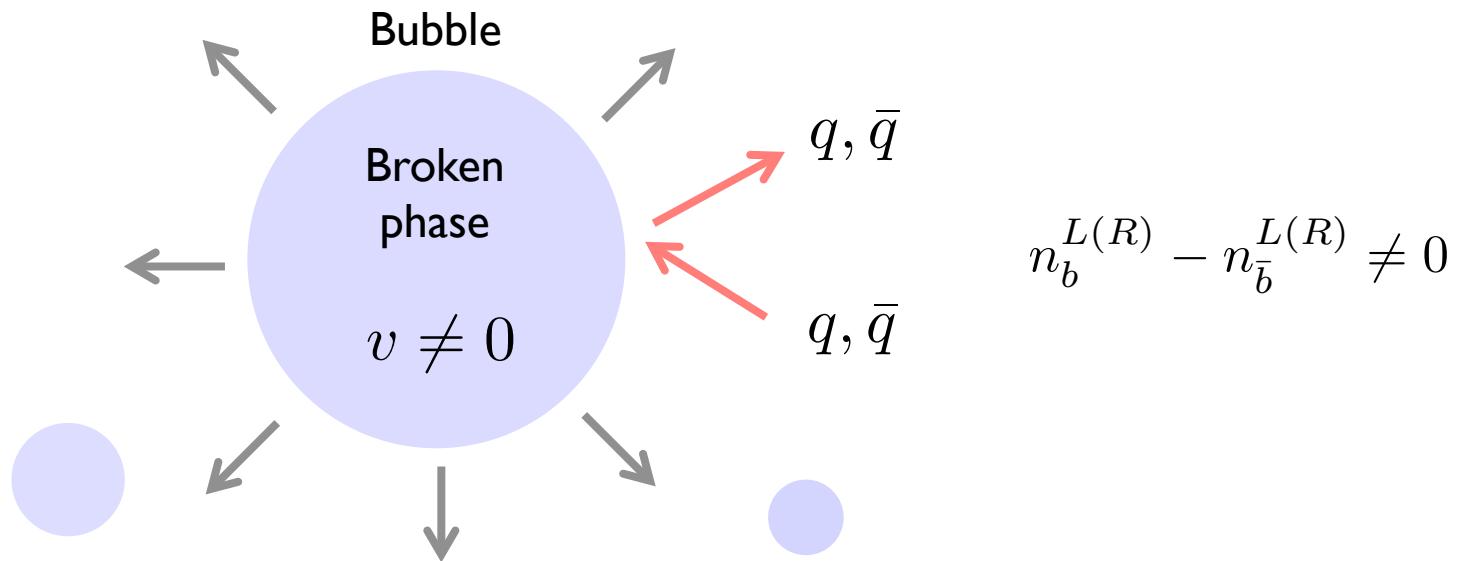


Boiling water

If EW phase transition is 1st order, bubbles can be nucleated.

Electroweak Baryogenesis

Baryon asymmetry is created during EW phase transition.



* Predict EDMs

Particle and antiparticle numbers can be different if CPV exists.

One example of BSM physics : Two Higgs Doublet Model

Two doublets H_1 and H_2

Yukawa interactions :

$$-\mathcal{L}_Y = \bar{q}_L \left(Y_1 \tilde{H}_1 + Y_2 \tilde{H}_2 \right) u_R + \text{h.c.}$$

Y_1, Y_2 : Complex numbers

$$H_{1,2} = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + ia_i) \end{pmatrix}$$

* 2HDM can cause the first-order EWPT.

K.Fuyuto, E. Senaha, PLB(2015)152,
K. Fuyuto, E. Senaha, CW. Chiang, PLB762(2016)315

Two Higgs Doublet Model

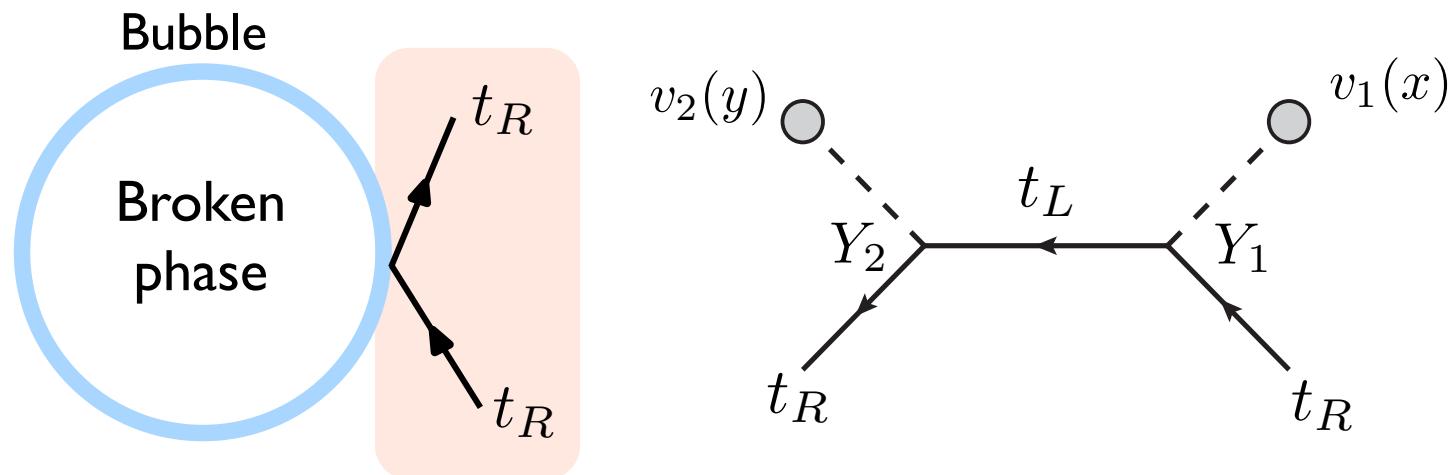
KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

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Two doublets H_1 and H_2

Yukawa interactions :

$$-\mathcal{L}_Y = \bar{q}_L \left(Y_1 v_1 + Y_2 v_2 \right) u_R + \text{h.c.}$$



* Focus on top quark

Two Higgs Doublet Model

KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

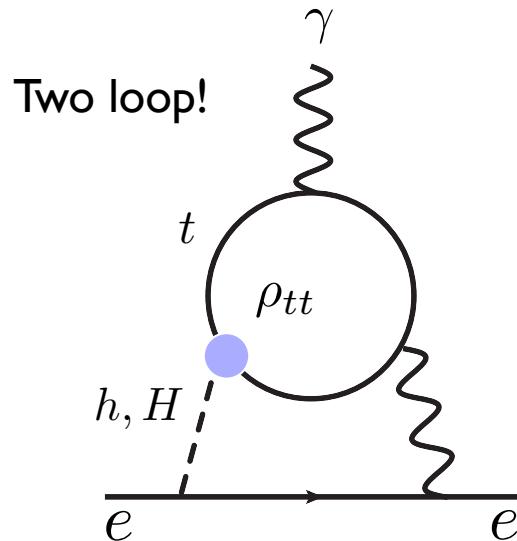
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Two doublets H_1 and H_2

Yukawa interactions :

Complex : $|\rho_{tt}|e^{i\phi_{tt}}$

$$-\mathcal{L}_Y = \bar{t}_L \left[\frac{y_t}{\sqrt{2}} s_\alpha + \frac{1}{\sqrt{2}} \rho_{tt} c_\alpha \right] t_R h + \text{h.c.}$$



BAU : $n_B \propto y_t |\rho_{tt}| \sin \phi_{tt}$

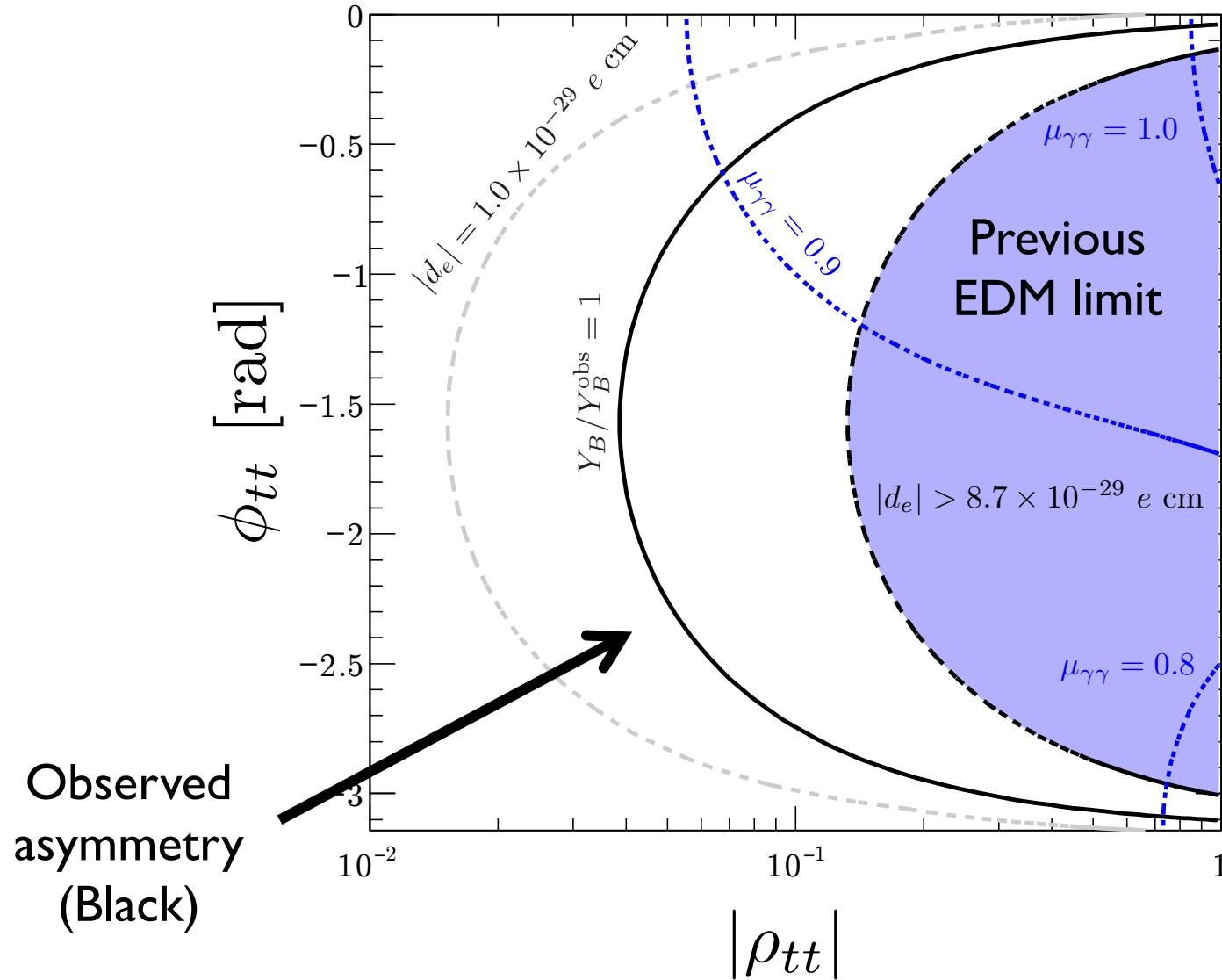
EDM : $d_e \propto |\rho_{tt}| \sin \phi_{tt}$

Probed by EDM experiments !

Two Higgs Doublet Model

KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

16



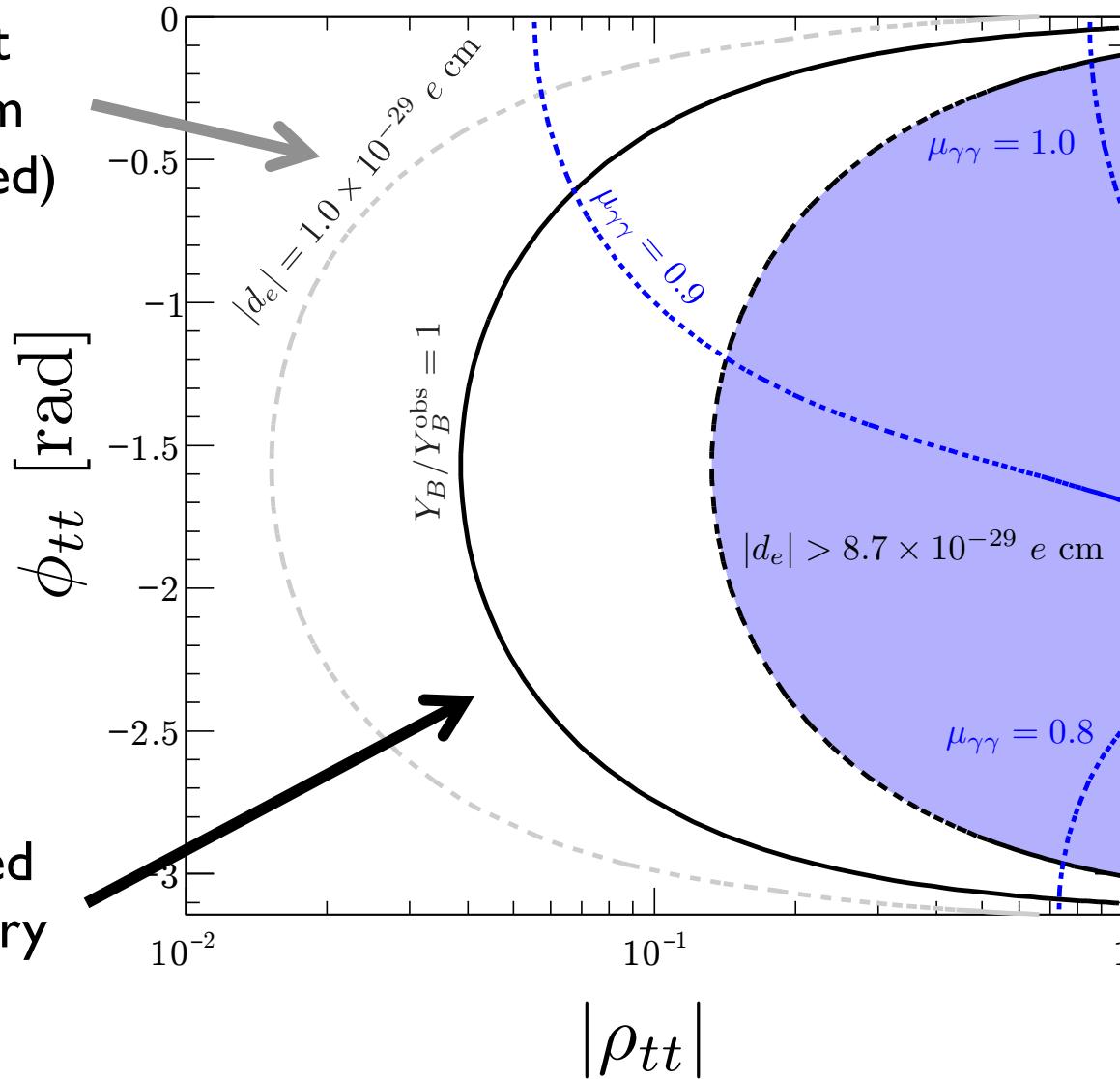
Two Higgs Doublet Model

KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

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New limit
 $\sim 10^{-29}$ e cm
(Gray dashed)

Observed
asymmetry
(Black)

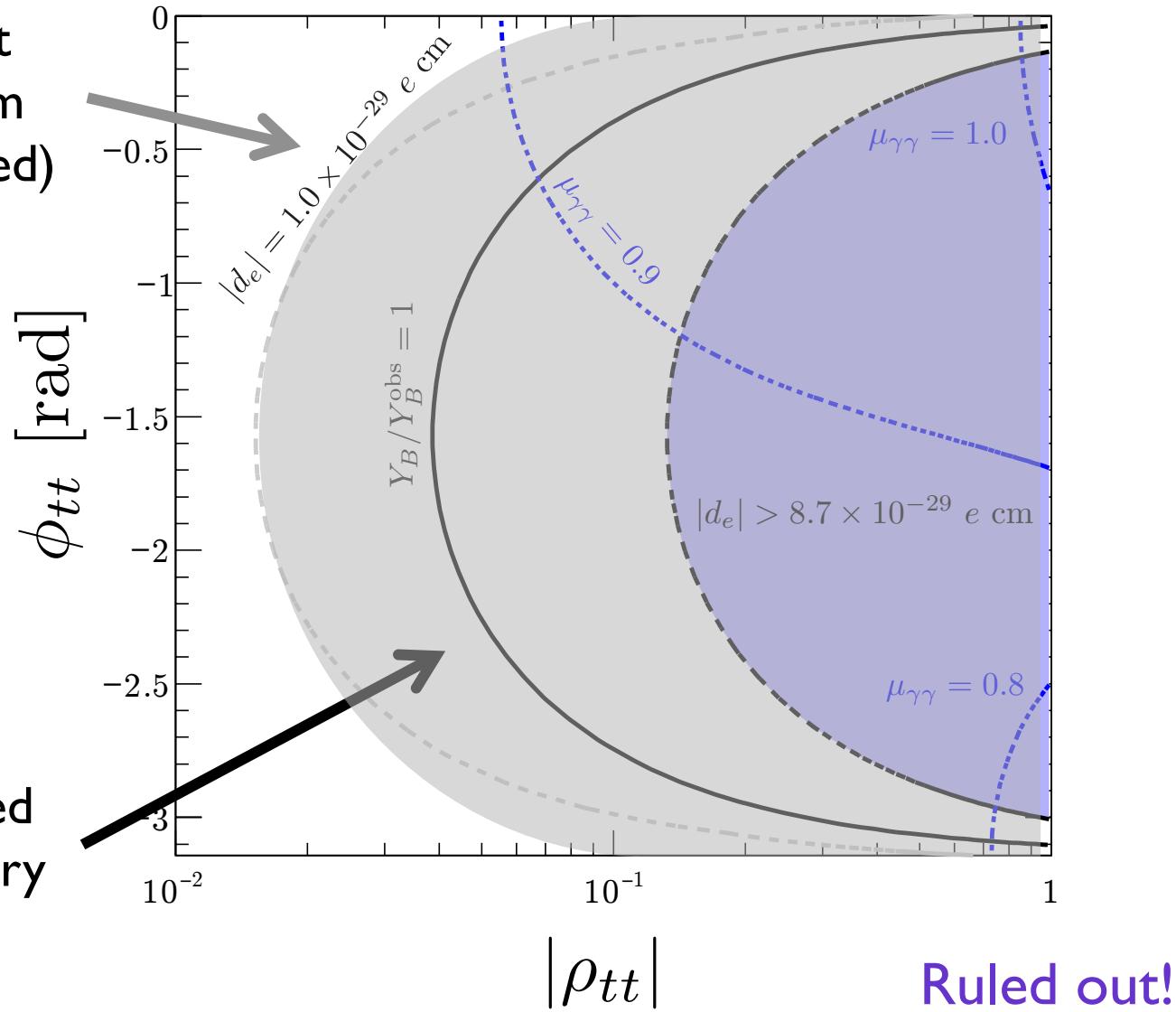


Two Higgs Doublet Model

KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

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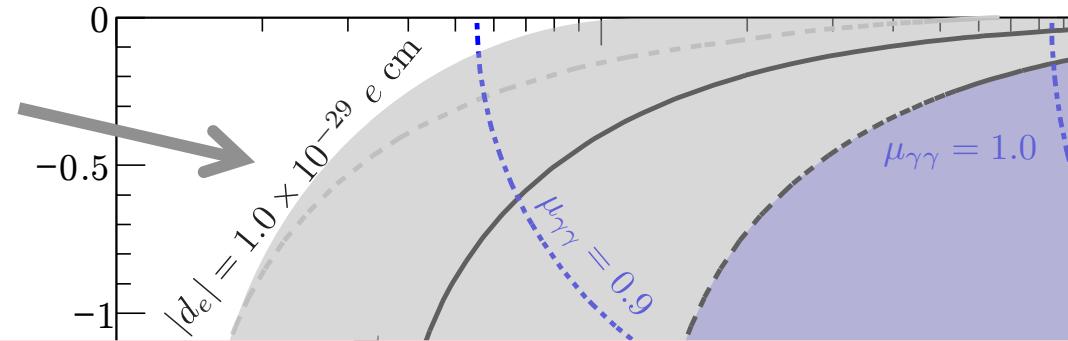
Observed
 asymmetry
 (Black)



Two Higgs Doublet Model

KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

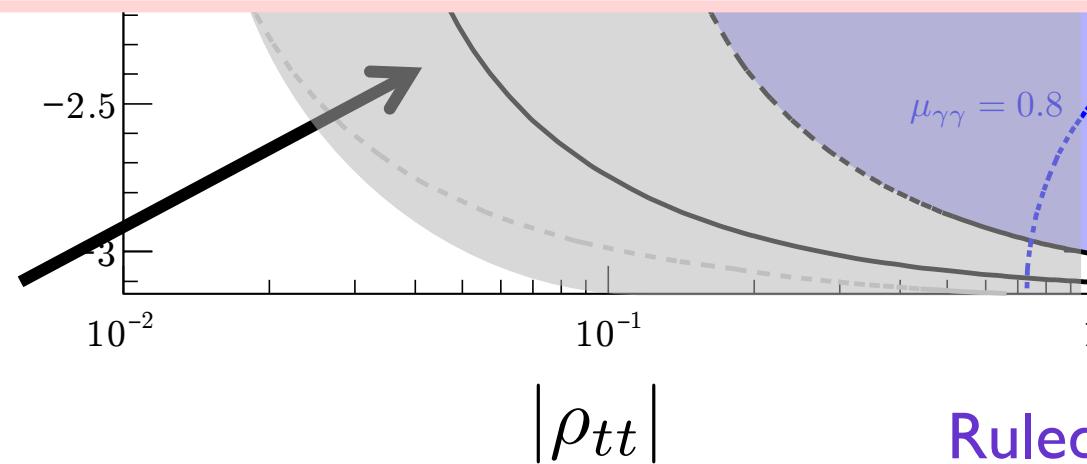
New limit
 $\sim 10^{-29}$ e cm
 (Gray dashed)



Focus on one CP phase : ρ_{tt}

What about a case with more phases?

Observed
 asymmetry
 (Black)



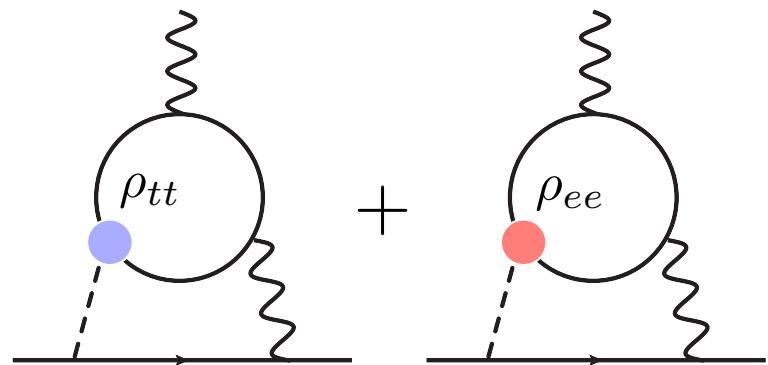
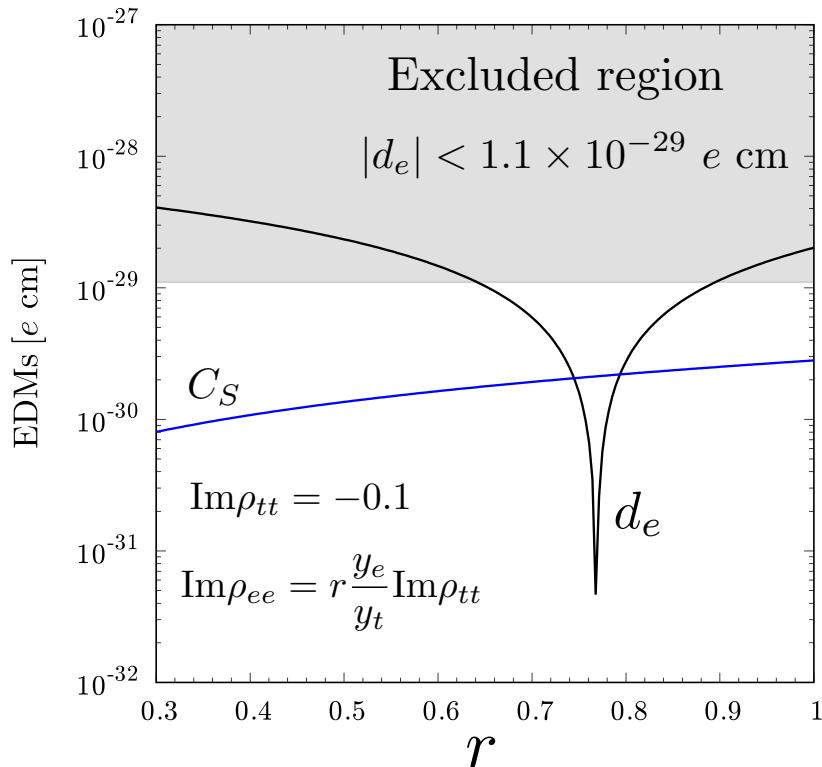
Ruled out!

Two Higgs Doublet Model

KF, WS. Hou, and E. Senaha, PRD 101(2020)011901

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Case with two phases : ρ_{tt} , ρ_{ee}



Cancellation occurs.

2HDM EWBG is still viable.

Multi-species searches, e.g. nucleon EDMs, are necessary!

Implication for DM candidate

Axion is one attractive *DM candidate*.

Strong CP problem : $\theta \lesssim 10^{-10}$ | $\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}$

Peccei-Quinn Symmetry to absorb θ into axion field : $\theta \rightarrow a/f_a$

R. Peccei and H. R. Quinn, Phys.Rev.Lett. 38 (1977) 1440

R. Peccei and H. R. Quinn, Phys.Rev. D16 (1977) 1791{1797.

S. Weinberg, PRL40(1978)223,

F. Wilczek, PRL40(1978)279

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R. Peccei and H. R. Quinn, Phys.Rev. D16 (1977) 1791{1797.

S. Weinberg, PRL40(1978)223,

F. Wilczek, PRL40(1978)279

Another (UV) solution : P or CP symmetry to set $\theta = 0$ at UV

A.E. Nelson, PLB136 (1984) 387,

S. M. Barr, PRD30(1984)1805, PRD30(1984)1805

L. Bento, et al, PLB267(1991)95

M. Beg, et al, PRL41(1978)278, R. N. Mohapatra, et al, PLB79(1978)283

H. Georgei, Hadronic J. I, 155 (1978), K. S. Babu and R. N. Mohapatra, PRD41(1990)1286

SM. Barr, et al, PRL67(1990)2765

Can we probe UV solution?

Implication for DM candidate

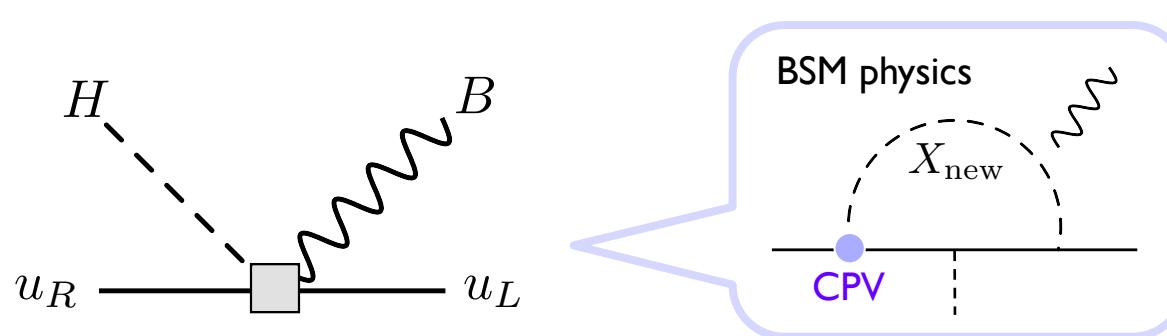
J. de Vries, P. Draper, **KF**, J. Kozaczuk, D. Sutherland,
PRD015042(2019)99

23

UV solutions can be probed by looking for new CP sources.

Ex) d = 6 up-quark dipole operator

$$\mathcal{O}_{uB} = \bar{Q}\sigma^{\mu\nu}u_R\tilde{H}B_{\mu\nu}$$



$$\text{Up-quark EDM: } d_u \sim \frac{v}{m_X^2} \text{Im}(C_{uB})$$

Implication for DM candidate

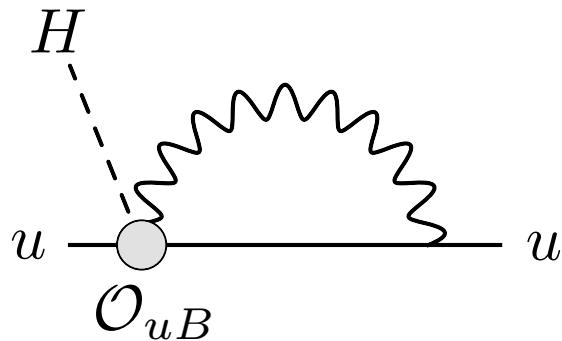
J. de Vries, P. Draper, **KF**, J. Kozaczuk, D. Sutherland,
PRD015042(2019)99

24

UV solutions can be probed by looking for new CP sources.

Ex) d = 6 up-quark dipole operator

$$\mathcal{O}_{uB} = \bar{Q}\sigma^{\mu\nu}u_R\tilde{H}B_{\mu\nu}$$



$$\Delta\theta \sim \frac{1}{16\pi^2\Lambda^2} \text{Im}(C_{uB}) \Lambda^2 \gg 10^{-10}$$

Quadratic divergence

If any new CPV interactions are present,
UV solutions would not work.

*Threshold corrections to theta from dim=6 operators + search for top cEDM at pp collider
J. de Vries, P. Draper, **KF**, J. Kozaczuk, D. Sutherland, PRD015042(2019)99

Implication for DM candidate

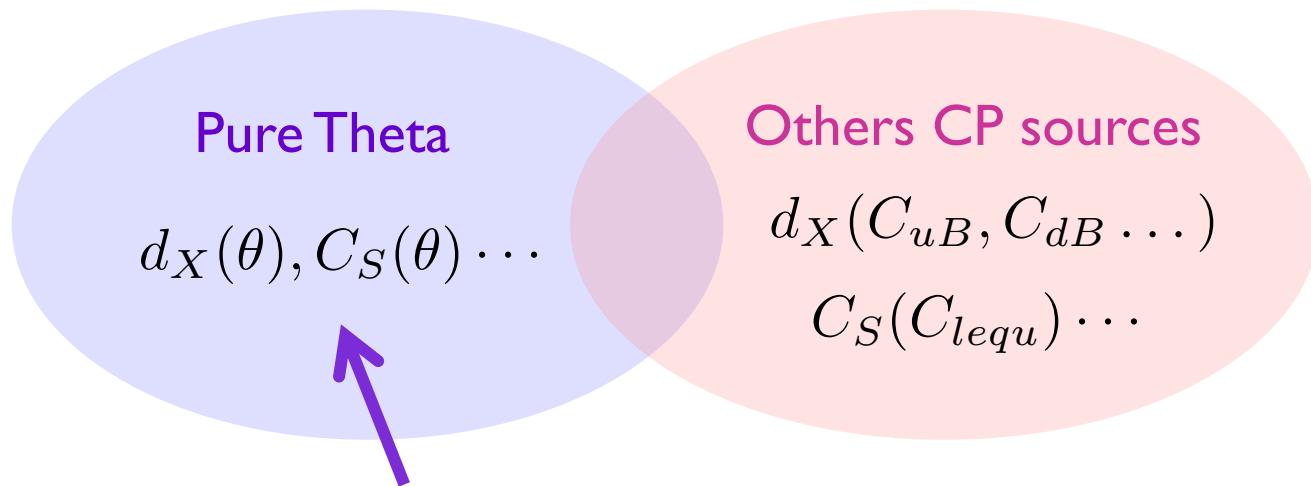
J. de Vries, P. Draper, **KF**, B. Lillard,
PRD104(2021)055039

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UV solutions can be probed by looking for new CP sources.

OR

by investigating “pure theta scenario”



Strategy : Rule out “pure theta scenario” with two EDMs

Predictions of EDMs in two scenario: Pure Theta vs BSM physics with another CPV

J. de Vries, P. Draper, **KF**, B. Lillard, PRD104(2021)055039

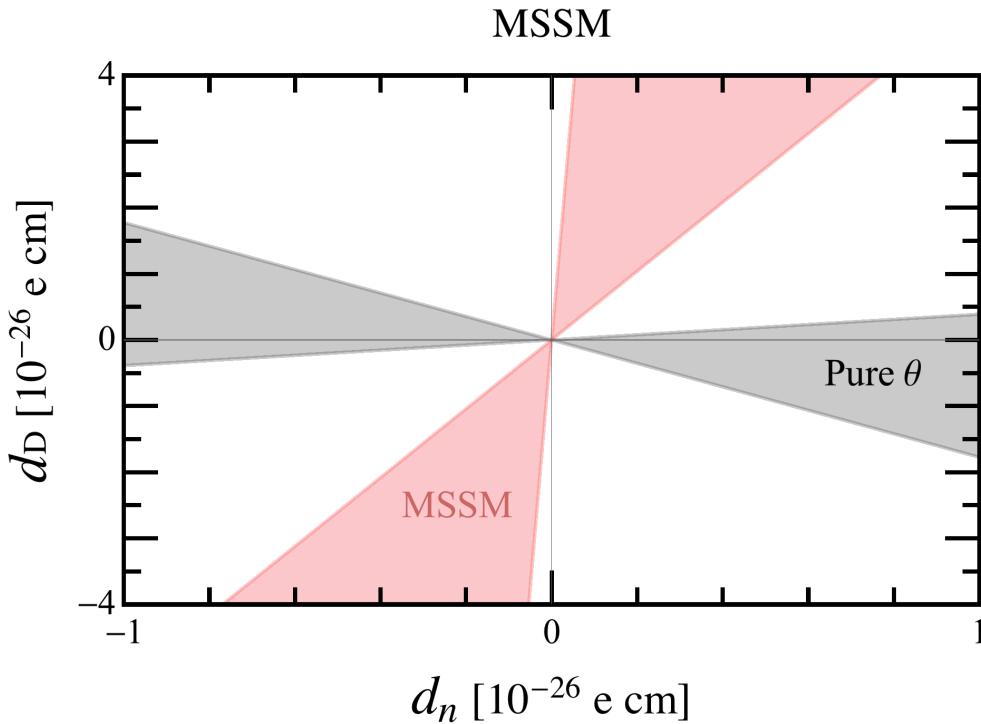
Neutron and Deuteron EDMs

J. de Vries, P. Draper, **KF**, B. Lillard,
PRD 104(2021)055039

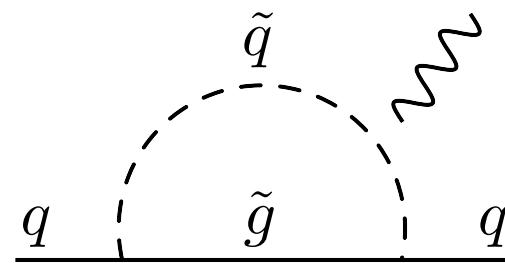
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(Gray) Pure Theta Scenario

(Pink) Minimal SUSY Model (gluino mass phase)



* Quark EDMs/cEDMs



The prediction of d_D/d_n is different from pure theta case.

Charged Lepton Flavor Violation

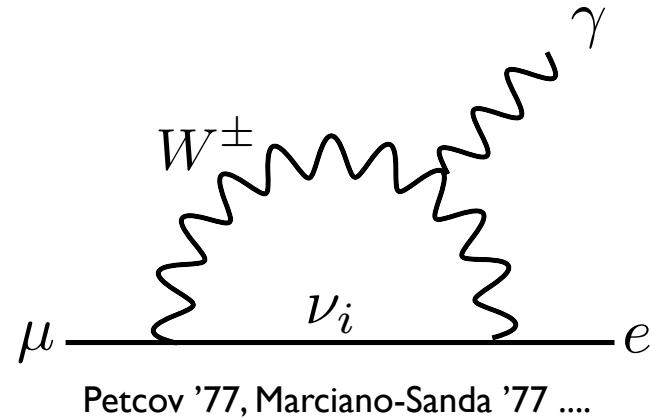
Charged Lepton Flavor Violation

Nonzero neutrino mass induces CLFV.

Ex) Minimal extension of the SM

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\nu-\text{mass}}$$

Dirac or Majorana



$$\text{Br}(\mu \rightarrow e\gamma) = \frac{3\alpha_{\text{em}}}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{m_W^2} \right|^2 < 10^{-54}$$

Extremely small!

The predicted BR is too small to be observed.

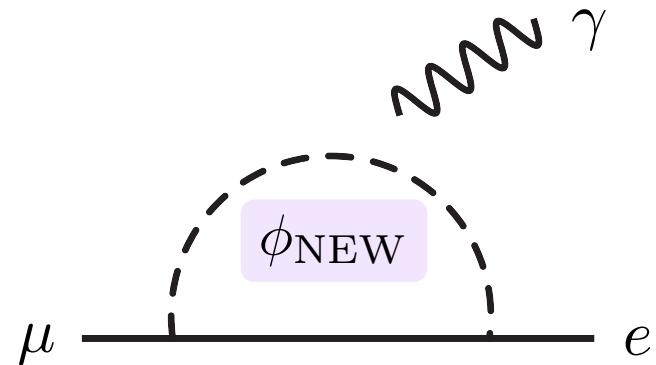
Charged Lepton Flavor Violation

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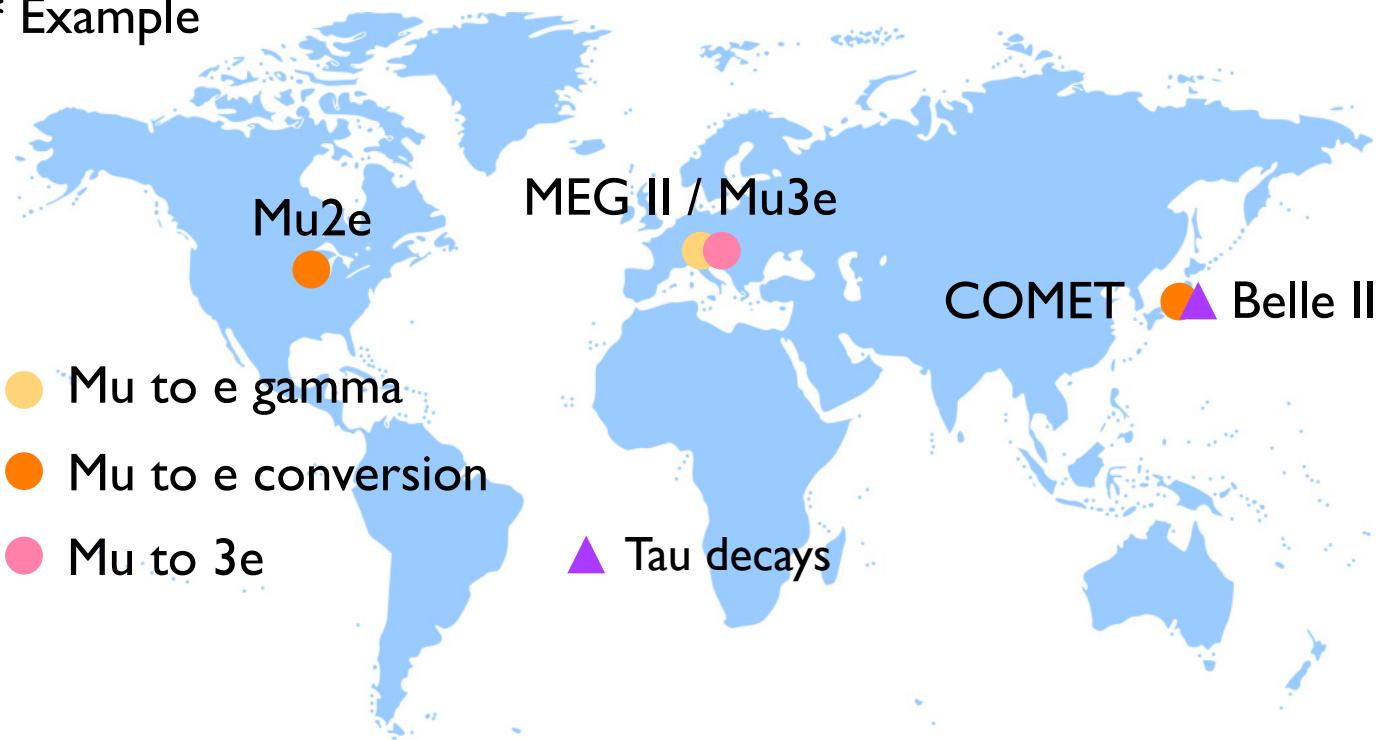
Extremely small!

The observation of CLFV would imply another contribution.

- ✓ Underlying physics, i.e., BSM physics

Searches for CLFV

* Example



$$\text{BR}(\mu^+ \rightarrow e^+ \gamma) < 4.2 \times 10^{-13}$$

MEG Collaboration, Eur. Phys. J. C 76(8), 434 (2016).

$$\text{BR}(\mu^- \text{ Au} \rightarrow e^- \text{ Au}) < 7 \times 10^{-13}$$

SINDRUM II, Eur. Phys. J. C 47(2), 337–346 (2006).

$$\text{BR}(\tau \rightarrow e\gamma) < 3.3 \times 10^{-8}$$

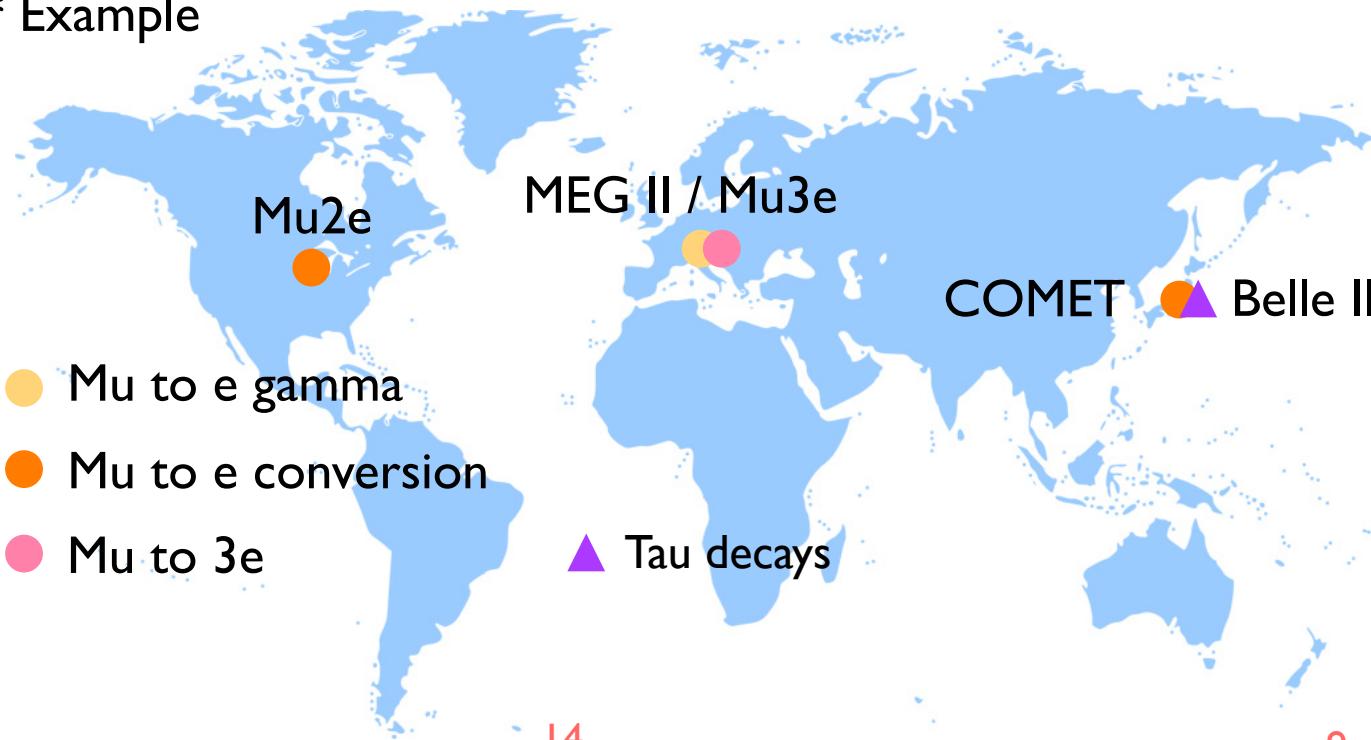
BaBar, PRL104 (2010) 021802

$$\text{BR}(\tau \rightarrow e\pi^+\pi^-) < 2.3 \times 10^{-8}$$

Belle, PLB719 (2013) 346-353

Searches for CLFV

* Example



$$\text{BR}(\mu^+ \rightarrow e^+ \gamma) < 4.2 \times 10^{-13}$$

MEG Collaboration, Eur. Phys. J. C 76(8), 434 (2016).

$$\text{BR}(\mu^- \text{ Au} \rightarrow e^- \text{ Au}) < 7 \times 10^{-17}$$

SINDRUM II, Eur. Phys. J. C 47(2), 337–346 (2006).

$$\text{BR}(\tau \rightarrow e\gamma) < 3.3 \times 10^{-9}$$

BaBar, PRL104 (2010) 021802

$$\text{BR}(\tau \rightarrow e\pi^+\pi^-) < 2.3 \times 10^{-8}$$

Belle, PLB719 (2013) 346-353

* Future

Electron-Ion Collider

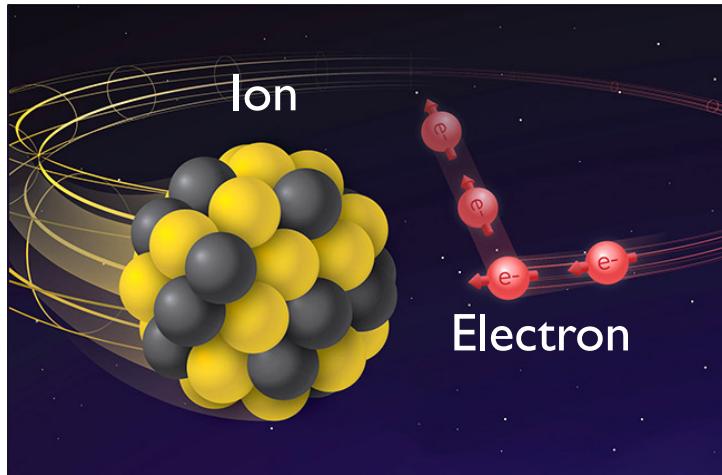
EIC Detector Requirements and R&D Handbook
EIC Yellow report, arXiv:2103.05419

32

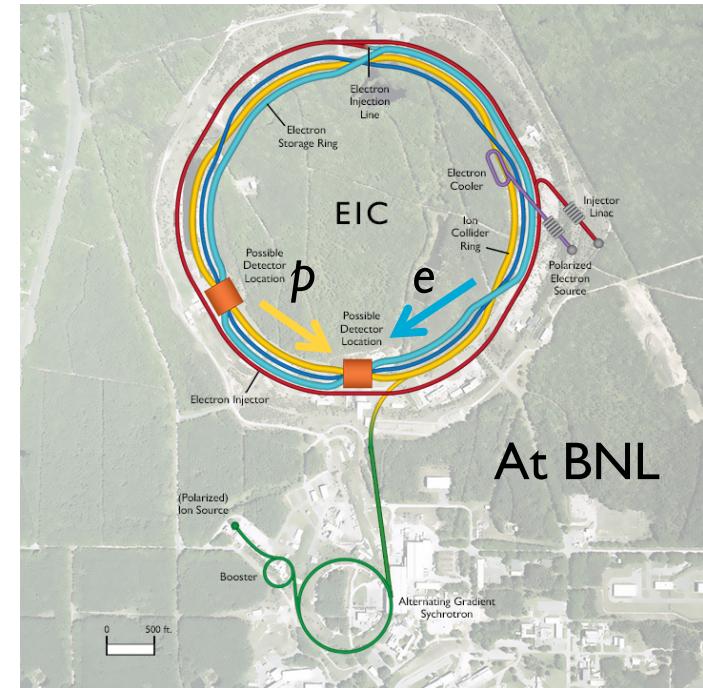


One potential probe : CLFV search at the EIC

DOE granted CD-0 to the EIC on January 9, 2020.



Collide electrons and protons/heavy ions



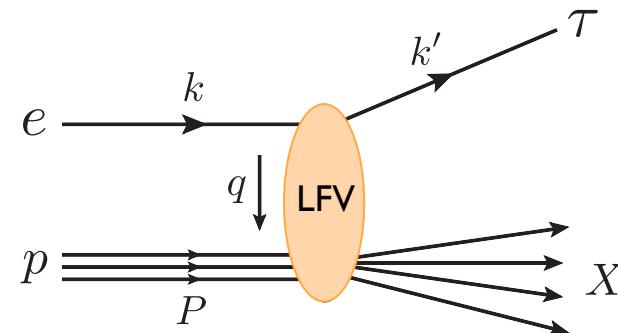
Map the structure of the proton and nuclei

- Electrons - protons/heavy ions collisions

$\sqrt{S} = 20 \sim 100 \text{ GeV}$ (Upgradable to 140 GeV)

- High Luminosity

$\mathcal{L} \sim 10^{33-34} \text{ cm}^{-2}\text{s}^{-1}$
(10-100 fb^{-1} per year)



(e.g. HERA $\sqrt{S} = 318 \text{ GeV}$, $\mathcal{L} = 1.4 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$)

Can the EIC compete with other searches for e-tau transition?

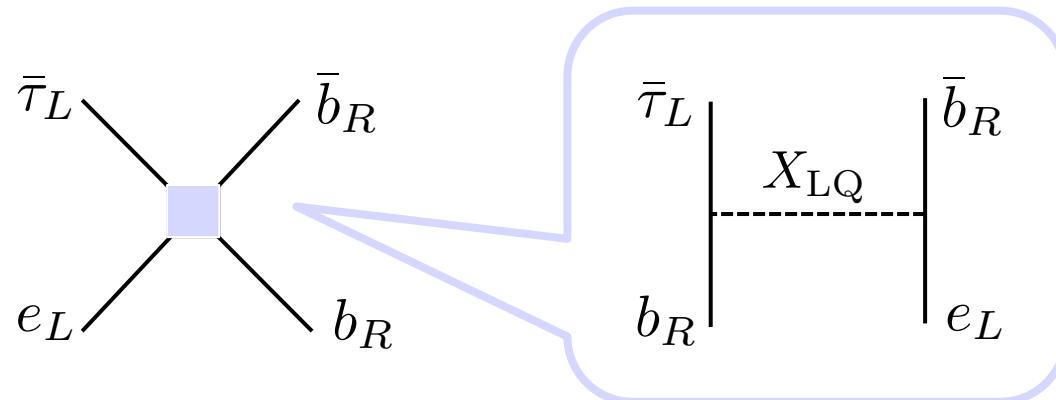
Model-independent (EFT) analysis + application to Leptoquark Model
V. Cirigliano, **KF**, C. Lee, E. Mereghetti, B. Yan, JHEP03(2021)256

Model-independent way : 16 different operators in total

Ex) Four-fermion vector operator

$$\mathcal{L} \supset -\frac{4G_F}{\sqrt{2}} [C_{Ld}]_{\tau ebb} \bar{\tau}_L \gamma^\mu e_L \bar{b}_R \gamma_\mu b_R \quad \text{VLR : bb element}$$

Ex) Induced by Scalar Leptoquark Model

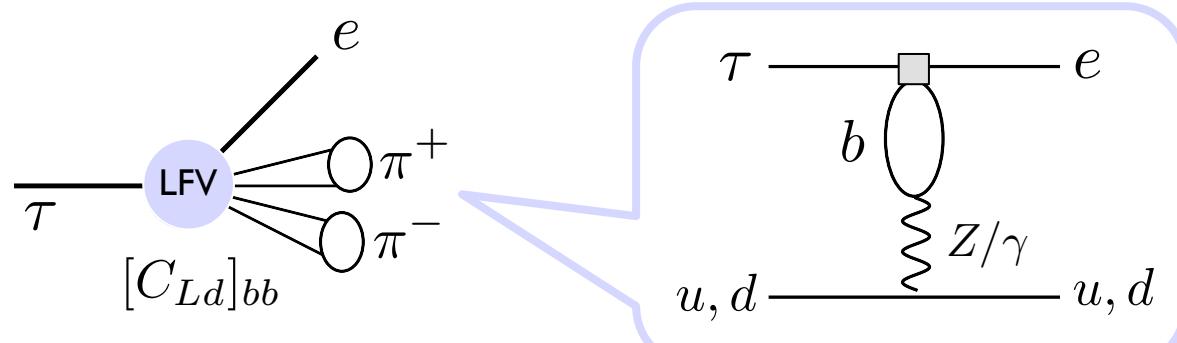


Model-independent way : 16 different operators in total

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Scale running effect : The renormalization group equation



$$\text{BR}(\tau \rightarrow e\pi^+\pi^-) < 2.3 \times 10^{-8}$$

Loop effect $\sim 10^{-3}$

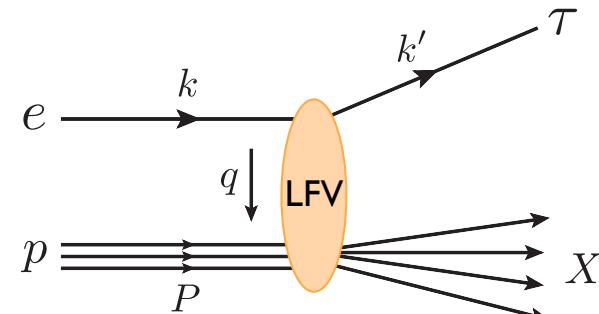
EIC analysis

V. Cirigliano, **KF**, C. Lee, E. Mereghetti, B. Yan
JHEP03(2021)256

- Cross sections : $\mathcal{O}(1 - 10)$ pb at $\sqrt{S} = 141$ GeV

- Major backgrounds

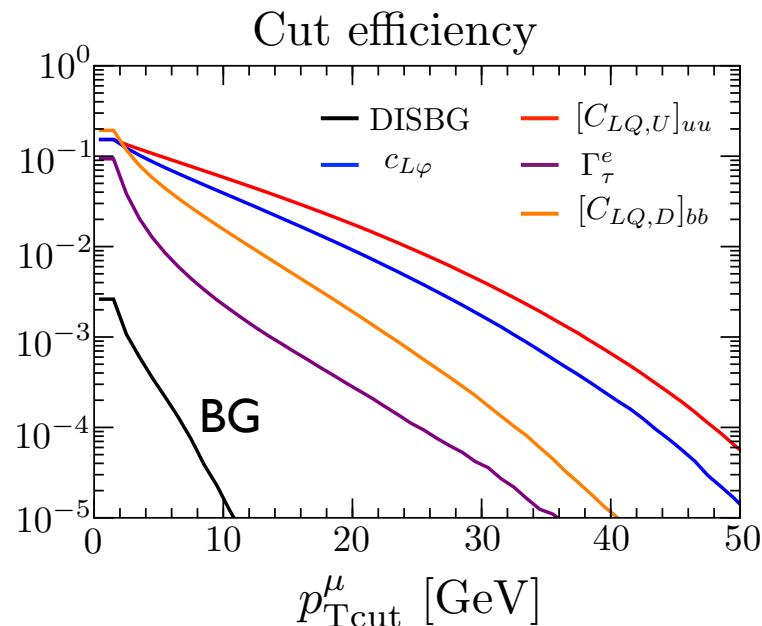
- 1) Neutral Current : $ep \rightarrow ej$
- 2) Charged Current : $ep \rightarrow \nu_e j$



- Promising channel

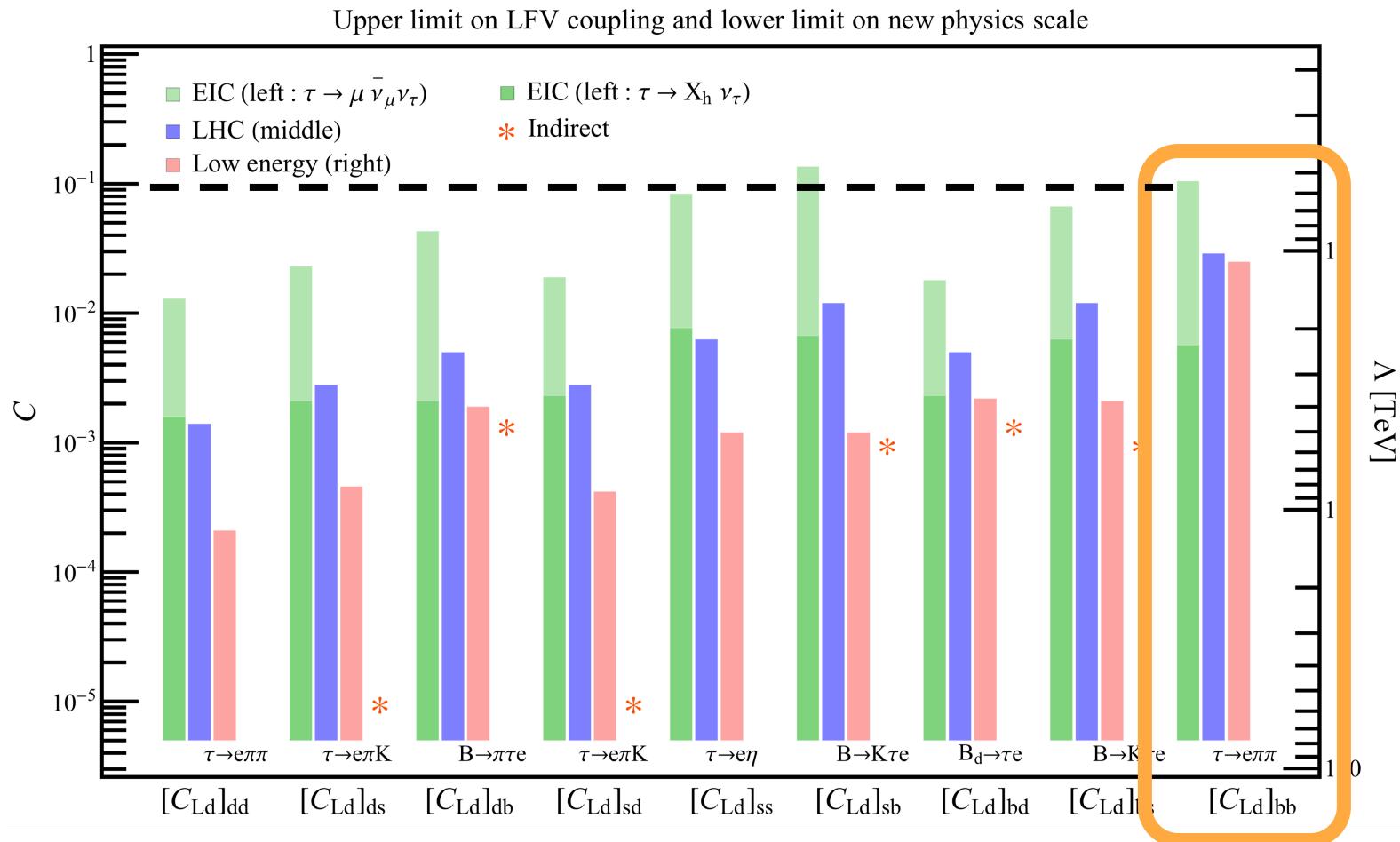
$$\text{BR}(\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau) = 17.39\%$$

- * Moderate cuts enable to eliminate all SM background



EIC vs Current limits

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EIC : $[C_{Ld}]_{bb} < 0.1$ **LHC, Tau decay** : $[C_{Ld}]_{bb} < O(10^{-2})$

Competitive!

Multi-operator scenario

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See the situation where 8 operators are nonzero

* Z couplings + down-type 4F operators

$$\mathcal{L}_{\text{LFV}} \supset -\frac{g_2}{c_W} \left(c_{L\varphi}^{(1)} + c_{L\varphi}^{(3)} \right) \bar{\tau}_L \gamma^\mu Z_\mu e_L$$

$$-\frac{4G_F}{\sqrt{2}} \sum_{a=d,s,b} [C_{Ld}]_{aa} \bar{\tau}_L \gamma^\mu e_L \bar{d}_{Ra} \gamma_\mu d_{Ra}$$

$$-\frac{4G_F}{\sqrt{2}} \sum_{a=d,s,b} [C_{LQ,D}]_{aa} \bar{\tau}_L \gamma^\mu e_L \bar{d}_{La} \gamma_\mu d_{La}$$

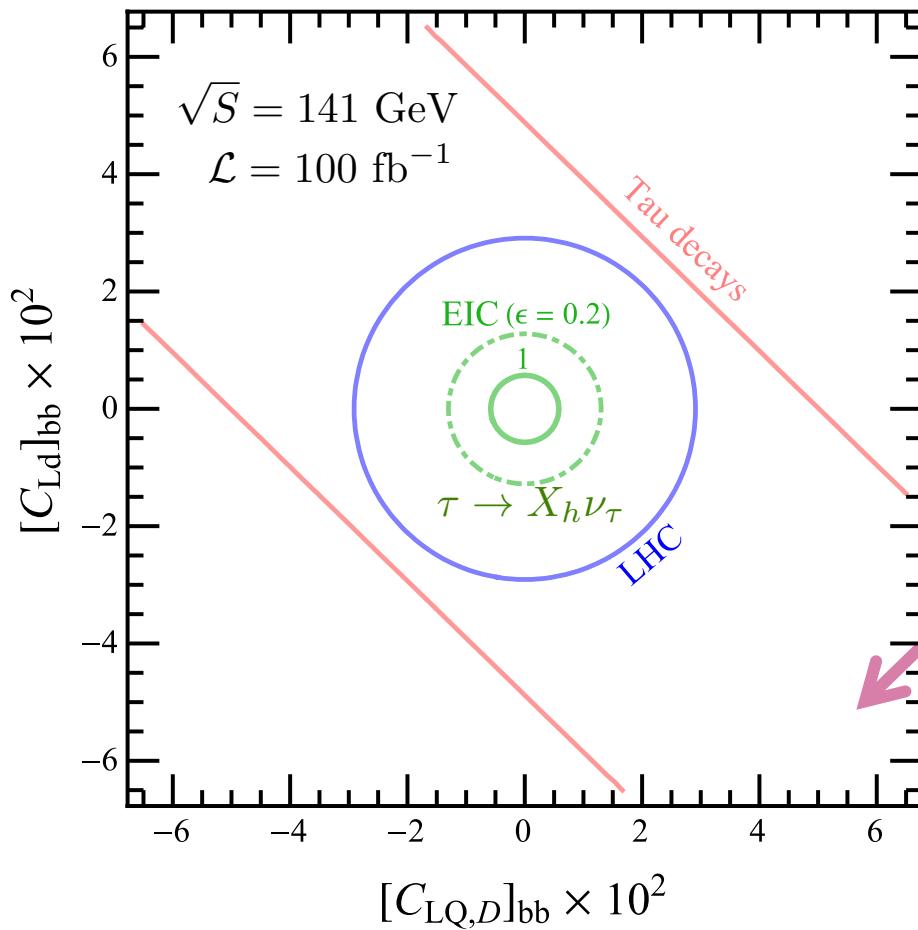
✓ Limits on $[C_{LQ,D}]_{bb}$ and $[C_{Ld}]_{bb}$ at 90% C.L.

The rest is marginalized.

Multi-operator scenario

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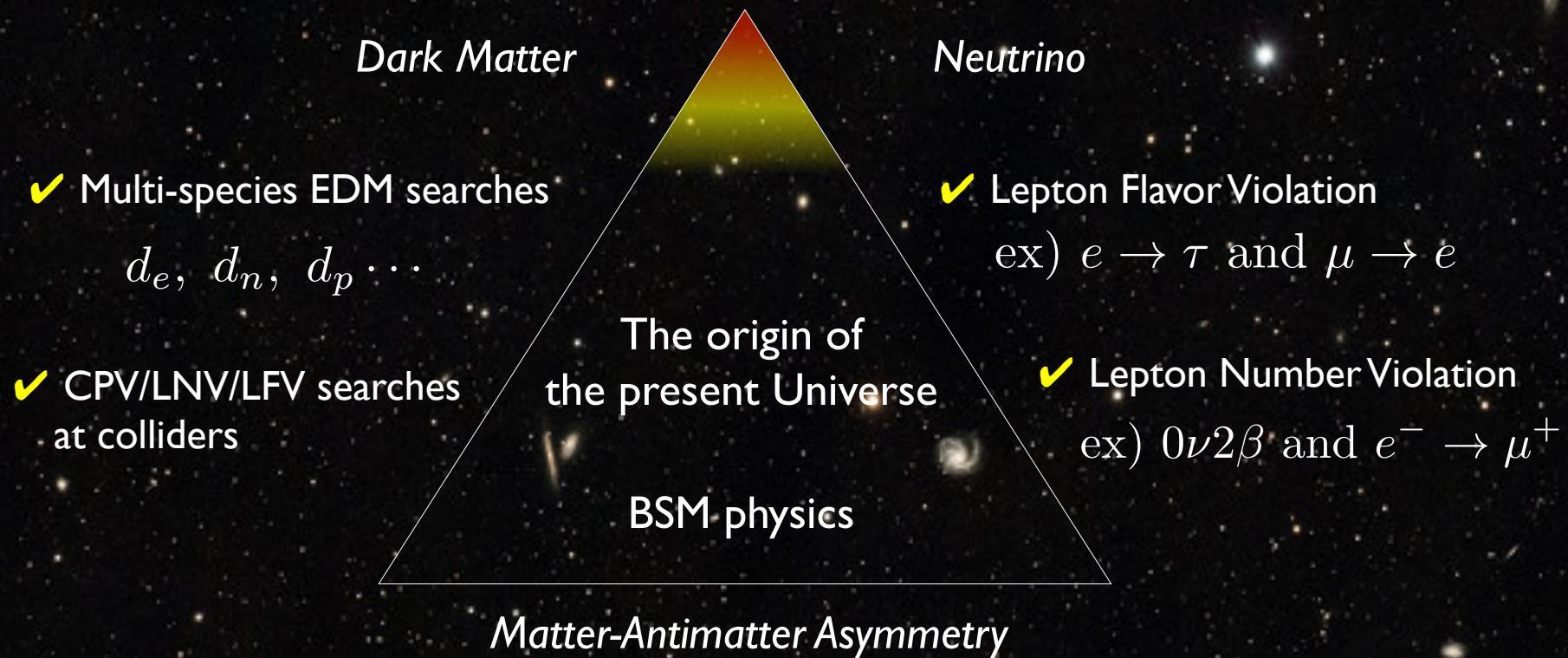
Free direction appears.

$$[C_{LQ,D}]_{bb} - [C_{Ld}]_{bb}$$

Collider probes are necessary to close the free direction.

Conclusion

We still don't know much about our Universe.



★ Various fundamental symmetry tests to reveal the origin of the Universe
* From low-energy to intensity and energy frontiers

Backup

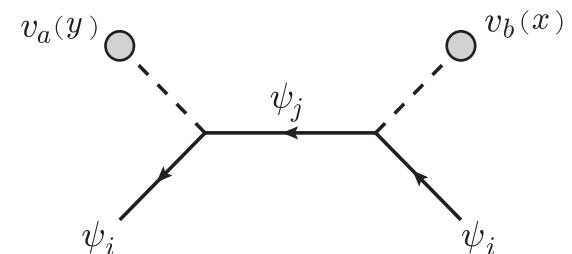
Future direction I

✓ Investigation of any possibility of CP violation

- CPV in various models beyond the Standard Model
- Multiple searches for new CP violation, e.g. collider experiments

✓ Improvement of theoretical uncertainties

- Estimations of the asymmetry
Beyond the lowest order in powers of v/T
- Nucleon EDMs
 - ~ 50% uncertainties from quark chromo EDMs
 - * Expect lattice QCD calculations



Future plan : $d_p \sim 10^{-29} \text{ e cm}$ $d_n \sim 10^{-28} \text{ e cm}$

Future direction II

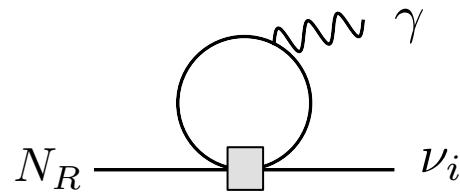
- ✓ Contributions from light sterile neutrinos to the BAU in model-independent way + concrete models

e.g., how LNV and LFV interactions affect the BAU

Impact of keV sterile neutrino (DM candidate)

- ✓ Implications for fundamental symmetry tests and cosmology

e.g., effects from LNV interactions on X ray/CMB observation



- ✓ Improvements of theoretical analysis of LNV/LFV mu to e conversion